EXHIBIT J

0022-3565/02/3011-241–248$7.00
THE JOURNAL OF PHARMACOLOGY AND EXPERIMENTAL THERAPEUTICS

JPET 301:241–248, 2002

Vol. 301, No. 1
4621/969729
Printed in U.S.A.

Pharmacological Profile of a Novel Phosphodiesterase 4 Inhibitor, 4-(8-Benzo[1,2,5]oxadiazol-5-yl-[1,7]naphthyridin-6-yl)-benzoic Acid (NVP-ABE171), a 1,7-Naphthyridine Derivative, with Anti-Inflammatory Activities

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Received October 8, 2001; accepted December 5, 2001 This article is available online at http://jpet.aspetjournals.org

ABSTRACT

We investigated the pharmacology of a new class of phosphodiesterase 4 (PDE4) inhibitor, 6,8-disubstituted 1,7-naphthyridines, by using 4-(8-benzo[1,2,5]oxadiazol-5-yl-[1,7]naphthyridin-6-yl)-benzoic acid (NVP-ABE171) as a representative compound and compared its potency with the most advanced PDE4 inhibitor, undergoing clinical trials, Ariflo [*cis*-4-cyano-4-(3-cyclopentyloxy-4-methoxyphenyl-*r*-1-cyclohexanecarboxylic acid)]. NVP-ABE171 inhibited the activity of phosphodiesterase 4A, 4B, 4C, and 4D with respective IC_{50} values of 602, 34, 1230, and 1.5 nM. Ariflo was about 40 times less potent. In human cells, NVP-ABE171 inhibited the eosinophil and neutrophil oxidative burst, the release of cytokines by T cells, and the tumor necrosis factor-α release from monocytes, in the nanomolar range. Ariflo presented a similar inhibition profile but was 7 to 50 times less potent. In BALB/c mice challenged with lipopolysaccharide, NVP-ABE171 inhibited the airway neutrophil influx and activation with an ED_{50} in the range of 3 mg/kg. Ariflo was inactive up to a dose of 10 mg/kg. In ovalbumin sensitized Brown Norway rats, NVP-ABE171 inhibited the lipopolysaccharide-induced airway neutrophil influx and activation (ED_{50} of 0.2 mg/kg) and the ovalbumin-induced airway eosinophil influx and activation (ED_{50} of 0.1 mg/kg). Ariflo was about 100 times less potent in both models. In the ovalbumin model, NVP-ABE171 had a duration of action of more than 24 h. NVP-ABE171 is a novel PDE4 inhibitor that shows activity both in vitro on human inflammatory cells and in vivo in animal models of lung inflammation. This compound class may have potential for the treatment of airway inflammatory conditions such as asthma and chronic obstructive pulmonary diseases.

3′,5′-Cyclic nucleotide phosphodiesterases (PDEs) are families of hydrolases that catalyze the hydrolysis of cAMP and cGMP, and thereby terminate their role as second messengers in mediating cellular responses to various mediators. Eleven families of PDE enzymes, sharing a conserved catalytic domain and exhibiting distinct substrate specificity and regulatory properties, have been identified (Soderling and Beavo, 2000). Among the cAMP-specific isoenzymes, PDE4s have received particular attention after the recognition that these are the primary enzymes responsible for the metabolism of cAMP in inflammatory and immune cells (Muller et al., 1996). Because PDE4 inhibitors have been shown to be potent anti-inflammatory agents in various animal models (Teixeira et al., 1997), they have been proposed as a new therapeutic approach for a variety of inflammatory diseases such as asthma and chronic obstructive pulmonary diseases (Barnes, 1999). Despite the large effort of the pharmaceutical industries to identify selective PDE4 inhibitors in the last decade, only a few of them have shown efficacy in patients, probably due to the fact that the clinical usefulness of these compounds is limited by adverse effects (i.e., nausea and emesis) (Teixeira et al., 1997). However, promising data from clinical trials with Ariflo, the most advanced PDE4 inhibitor in clinical development, support the concept that a dissociation of side effects from therapeutic benefit can be achieved with this class of drug (Torphy et al., 1999).

Recently, different isogenes and splice variants of human PDE4 have been described (Beavo, 1995). The four gene products (PDE4A, 4B, 4C, and 4D) are characterized by their selective, high-affinity hydrolysis of cAMP and sensitivity to inhibition by rolipram. According to an analysis of a number of human peripheral blood cells and cell lines, mRNA of these

ABBREVIATIONS: PDE, phosphodiesterase; NVP-ABE171, 4-(8-benzo[1,2,5]oxadiazol-5-yl-[1,7]naphthyridin-6-yl)-benzoic acid; DMSO, dimethyl sulfoxide; FCS, fetal calf serum; PBS, phosphate-buffered saline; IL, interleukin; IFN, interferon; ELISA, enzyme-linked immunosorbent assay; TNF, tumor necrosis factor; LPS, lipopolysaccharide; Ariflo, *cis*-4-cyano-4-(3-cyclopentyloxy-4-methoxyphenyl-*r*-1-cyclohexanecarboxylic acid); V 11294A, 3-(3-cyclopentyloxy-4-methoxybenzyl)-6-ethylamino-8-isopropyl-3*H*-purine hydrochloride; YM976, 4-3(chlorophenyl-1,7-diethylpyrido[2,3-*d*]pyrimidin-2(1*H*)-one; LAS 31025, 3-(*p*-chlorophenyl)-1-propylxanthine; TES, 2-{[2-hydroxy-1,1-bis(hydroxymethyl)ethyl]amino}ethanesulfonic acid.

isoforms is expressed in the majority of the immune and inflammatory cells (Muller et al., 1996). In particular, PDE4A, 4B, and 4D were predominantly expressed in eosinophils and neutrophils, whereas PDE4C mRNA was not detected in any of the inflammatory cells tested. Our research efforts in finding novel PDE4 inhibitors were based upon a new approach. We wanted to find orally active, second-generation PDE4 inhibitors displaying different selectivity profiles against the PDE4 isozymes (Hersperger et al., 2000). In this report we investigate the in vitro and in vivo anti-inflammatory properties of 4-(8-benzo[1,2,5]oxadiazol-5-yl-[1,7]naphthyridin-6-yl)-benzoic acid (NVP-ABE171), an inhibitor for the PDE4B and 4D isozymes. Ariflo, V 11294A, and LAS 31025 were used as comparison compounds.

Materials and Methods

Inhibition of Nucleotide Phosphodiesterase Isoenzymes. Phosphodiesterase activity was determined as previously described using cAMP or cGMP as substrate (Engels et al., 1995). Inhibitors were dissolved in dimethyl sulfoxide (DMSO) and diluted to the required concentration with the assay buffer containing DMSO at a final concentration of 0.5%. DMSO itself, at the concentration used, did not affect any of the PDE activity.

PDE1 was purified from human lung obtained from patients undergoing surgery for lung cancer. Tissue specimens were homogenized in Tris buffer, pH 7.4, containing 0.25 M sucrose, 1 mM EDTA, 1 mM dithiothreitol, 7 mg/ml phenylmethylsulfonyl fluoride, 10 μg/ml leupeptin, and 10 μg/ml pepstatin (TES).

PDE2 and 5 were purified from platelet concentrate obtained from the local blood transfusion center. Platelets were suspended in TES buffer and sonicated four times for 15 s at 4°C. Both preparations were centrifuged (120,000*g* for 60 min) and filtrated over a 0.22-μm filter. The resulting homogenate was applied to a 20-ml column of Q-Sepharose (Amersham Biosciences AB, Uppsala, Sweden) equilibrated in sucrose-free TES buffer. Upon elution with a gradient of 0 to 0.45 M NaCl, PDE1 was obtained as the calcium-calmodulin-stimulated peak of activity. PDE2 was obtained as the peak of activity by using 100 μM cAMP and PDE5 as a peak of activity by using 100 μM cGMP. Purification of human PDE3 and cloning and expression of human PDE4A, 4C, 4D, and rat PDE4B were performed as previously described (Hersperger et al., 2000). Pooled active fractions of each enzyme were made in ethylene glycol and stored at −20°C.

Permeability across Caco-2 Cells. Caco-2 cells, a colonic adenocarcinoma cell line, were seeded at a density of 10^5 cells/cm^2 onto transwell filter inserts (1 cm^2) and held in culture for 21 days. Test compounds were added to the donor compartment and aliquots were taken from the acceptor compartment and replaced with equal volume of blank medium at different time points. [^{3}H]Propranolol was used as a reference compound for transcellular transport. Levels of NVP-ABE171 were analyzed by high-performance liquid chromatography/UV detection.

Measurement of Intracellular cAMP Elevation in HaCat Cells. cAMP elevation studies were conducted in human keratinocyte cell line, HaCat. Cells (2.5×10^5) were allowed to adhere overnight to 24-well tissue culture plates at 37°C in 0.5 ml of medium [Dulbecco's modified Eagle's medium-H21 containing 5% fetal calf serum (FCS) and 2 mM L-glutamine]. Medium was removed and fresh medium containing 0.03 μM isoprenaline (Sigma-Aldrich, Poole, Dorset, UK) was added for 4 h. The reaction was stopped by the addition of 2 volumes of cold ethanol (−20°C). After a 15-min incubation at 4°C, the samples were centrifuged (450*g* for 10 min) and levels of cAMP in the supernatant measured by cAMP enzyme-linked immunosorbent assay kits (Amersham plc, Little Chalfont, Buckinghamshire, UK). For all the cell-based assays, test compounds or vehicle were preincubated for 15 min at 37°C.

Oxidative Burst from Human Eosinophils and Neutrophils. Blood was obtained from normal individuals. Granulocytes were separated from mononuclear cells by Ficoll-Hypaque gradient centrifugation. Erythrocytes were lysed by two cycles of hypotonic lysis and the remaining granulocytes were either used as enriched neutrophil preparation (>95% neutrophils) or incubated with anti-CD16-coated immunomagnetic particles. Magnetically labeled neutrophils were then depleted by passing the granulocytes through a magnetic cell separation column, which resulted in a more than 98% pure eosinophil preparation. Purified eosinophils or neutrophils (5×10^4/well in RPMI-1640 containing 0.1% human serum albumin) were stimulated with plate-bound human IgG (Sandoglobin-coated 96-well microtiter plates, 50 μg/well) or 1 μM *N*-formyl-methionyl-leucyl-phenylalanine, respectively, and the ability of cells to generate superoxide anions during an oxidative burst was measured using a Hamamatsu MTP reader. The IgG-induced changes in lucigenin chemiluminescence was monitored over 40 min and results were calculated as percentage of IgG- or *N*-formyl-methionyl-leucyl-phenylalanine-induced luminescence in the absence of compounds.

Proliferation and Cytokine Production of Human Peripheral Blood Lymphocytes. Mononuclear cells were isolated from blood of normal individuals by Ficoll-Hypaque gradient centrifugation (20 min at 800*g*). The interphase was collected, washed twice in phosphate-buffered saline (PBS), and resuspended in RPMI-1640 supplemented with 10% FCS. Cell density was adjusted to 10^6 cell/ml. One hundred microliters of the mononuclear cells suspension was placed in 96-well culture plates and 50 μl of either medium or compounds in the indicated concentrations was added. After a 10-min preincubation, cells were stimulated with 50 μl of anti-CD3 monoclonal antibodies (OKT-3, 100 ng/ml), incubated for 42 h at 37°C in a humidified incubator with 5% CO_2. Supernatants were harvested after 20 h of incubation. IL-4, IL-5, and IFN-γ were measured by sandwich ELISA by using two monoclonal antibodies recognizing different epitopes of the specific cytokine. Antibodies used for measuring cytokine levels were purchased from PharMingen (San Diego, CA). In all cases, binding of the second antibody was analyzed by stepwise incubation with streptavidin-alkaline phosphatase conjugate (Sigma-Aldrich) and 4-nitrophenylphosphate disodium salts (Sigma-Aldrich). Optical density was measured at 405 nm and cytokine concentration was calculated based on the results from serial dilutions of standard recombinant human IL-4, IL-5, and IFN-γ, respectively. The sensitivity of the cytokine ELISAs was 10 pg/ml.

TNF-α Production by Human Peripheral Blood Mononuclear Cells. Mononuclear cells were isolated as described above and resuspended in RPMI-1640 supplemented with 10% FCS. Cell density was adjusted to 10^6 cell/ml. Cells were stimulated with 10 μg/ml lipopolysaccharide (LPS; *Salmonella typhosa*) and 50 ng/ml IFN-γ and supernatants were harvested after 20 h of incubation at 37°C in a humidified incubator with 5% CO_2. Concentration of TNF-α in the supernatants was measured by sandwich ELISA by using two monoclonal antibodies recognizing different epitopes of the specific cytokine (mAb357/101-4 and biotinylated 2-179/E11; Novartis, Basel, Switzerland). Binding of the second antibody was analyzed by stepwise incubation with streptavidin-alkaline phosphatase conjugate (Mabtech, Stockholm, Sweden) and 4-nitrophenylphosphate disodium salt (Sigma-Aldrich). Optical density was measured at 405 nm and cytokine concentration was calculated based on the results from serial dilutions of standard recombinant human TNF-α.

Animals. The animals were housed in plastic cages in air-conditioned room at 24°C in a 12-h light/dark cycle. Food and water were available ad libitum. The studies reported herein conformed to the UK Animals (scientific procedures) Act 1986.

LPS-Induced Lung Inflammation in BALB/c Mice. Female BALB/c mice (5 weeks old) were treated intranasally, under halothane/oxygen/nitrous oxide anesthesia, with 0.3 mg/kg LPS (*Salmonella typhosa*; Sigma-Aldrich) in 50 μl of sterile PBS or with sterile PBS alone. Three or 24 h after the provocation, anesthesia was

induced with 60 m/kg i.p. pentobarbitone sodium. After anesthesia, the abdominal cavity was opened and the animal exsanguinated by withdrawal of blood from a major blood vessel. The trachea was cannulated and bronchoalveolar lavage was performed by injecting 4 × 0.3 ml of PBS into the lung via the trachea. The fluid was immediately withdrawn and the cell suspension stored on ice. Total cell count was measured and cytospin preparation (Shandon Scientific Ltd, Cheshire, UK) prepared. Cells were stained with Dif-Quick (Baxter Dade AG, Dudingen, Switzerland) and a differential count of 200 cells performed using standard morphological criteria. The remaining lavage fluid was centrifuged at 200*g* for 10 min, and the supernatant was either used fresh or aliquoted and stored at −80°C.

Ovalbumin-Induced Lung Inflammation in Brown Norway Rats. Animals were sensitized as described (Hannon et al., 2001). Briefly, 20 μg/ml ovalbumin was mixed with 20 mg/ml aluminum hydroxide and injected (0.5 ml/animal s.c.) coincidentally with Acullulare pertussis adsorbat vaccine (0.2 ml/animal i.p.; diluted 1:4 with 0.9% saline). Injection of ovalbumin, together with adjuvant, was repeated 14 and 21 days later. On day 28, sensitized animals were restrained in plastic tubes and exposed for 1 h to an aerosol of 3.2 mg/ml ovalbumin by using a nose-only exposure system. Animals were killed 48 h later with 250 mg/kg i.p. pentobarbital. The lungs were lavaged using three aliquots (4 ml) of Hanks' solution, recovered cells were pooled, and the total volume of recovered fluid adjusted to 12 ml by addition of Hanks' solution. Differential cell counts were done as described for the mice.

LPS-Induced Lung Inflammation in Brown Norway Rats. Ovalbumin-sensitized animals were challenged intratracheally with LPS (*Salmonella typhosa*, 10 μg/kg), on day 28 and killed 24 h later with 250 mg/kg, i.p. pentobarbital. The lungs were lavaged as described above.

Bronchoalveolar Lavage Soluble Mediators Measurements. Myeloperoxidase activity was measured on fresh bronchoalveolar lavage supernatant using a 96-well plate format colorimetric assay. Fifty microliters of the samples, in duplicate, were mixed with 100 μl of the substrate buffer for 5 min at room temperature (50 mM sodium phosphate, pH 6.0, containing, 0.5% hexadecyltrimethylammonium bromide, 0.167 nM *O*-dianiside dihydrochloride, and 0.4 mM H_2O_2). The reaction was stopped with 100 μl of 5% sodium azide in distilled water and the optical density read at 450 nm. Results were expressed as units per milliliter by using a standard curve established with human leukocyte myeloperoxidase (Sigma-Aldrich).

Eosinophil peroxidase activity was measure on fresh bronchoalveolar lavage supernatant by using a 96-well plate format colorimetric assay. Bronchoalveolar lavage (50 μl) was mixed with 100 μl of substrate (1 mM *o*-phenylenediamine dihydrochloride, 1 mM H_2O_2, 0.1% Triton X-100, dissolved in 50 mM Tris-HCl pH 7.7) in a 96-well flat-bottomed microtiter plate and incubated for 30 min at room temperature. The reaction was stopped by adding 50 μl of 4 M H_2SO_4 and absorbance was measured at 492 nm in a microtiter plate absorbance spectrophotometer. The concentration of eosinophil peroxidase activity was calculated as milliunits per milliliter according to the activity of serial dilutions of a standard horseradish peroxidase (Sigma-Aldrich).

The concentration of protein in bronchoalveolar lavage fluid supernatants was measured by a colorimetric assay (Bio-Rad DC protein assay) as described by the manufacturer (Bio-Rad, Hercules, CA). TNF-α levels were measured on bronchoalveolar lavage supernatant by using commercially available ELISA kits (Genzyme, Cambridge, UK).

Drug Administration. For in vivo testing, compounds were dissolved in DMSO (4% final concentration) and diluted with Neoral placebo for administration by gavage. Compounds or vehicle were applied 1 h before and 6 h after the LPS exposure in the mice, 1 h before the LPS exposure in the rat, and 1 h before and 24 h after the ovalbumin challenge in the rat. For the duration of action experiment, in the rat ovalbumin challenge model, animals were treated from 1 to 24 h before the challenge.

Data Analysis. Data are expressed as mean ± S.E.M. Statistical comparisons were performed using a Kruskall-Wallis test with Bonferroni's correction for multiple comparison, and a P value of less than 0.05 was considered significant. Depending on the efficacy of the compounds in the various test systems, corresponding IC or ED values for half-maximum inhibition were calculated from dose-dependent curves by nonlinear regression analysis. For cAMP elevation, EC_{200} was calculated as the concentration that doubled (200%) the level of cAMP induced by isoprenaline.

Results

Inhibition of Purified PDE Isozymes. Ariflo, V 11294A, LAS 31025, and NVP-ABE171 were synthesized by the Department of Chemistry (Novartis Pharmaceuticals, Horsham, UK). The structure of NVP-ABE171 is shown in Fig. 1. NVP-ABE171 and Ariflo dose dependently inhibited metabolic activity of the PDE4 isozymes; however, NVP-ABE171 was about 40-fold more potent than Ariflo. V 11294A and LAS 31025 inhibited the PDE4 isozymes only in the micromolar range. None of the compounds were active on all the other PDEs tested (i.e., PDE1, 2, 3, and 5) (Table 1).

Caco-2 Permeability and Intracellular cAMP Accumulation in HaCat Cells. In the Caco-2 assay NVP-ABE171 had a permeability coefficient value of 208.7 ± 24.1 10^{-5} cm/s (n = 4), well above the reference compound pro-

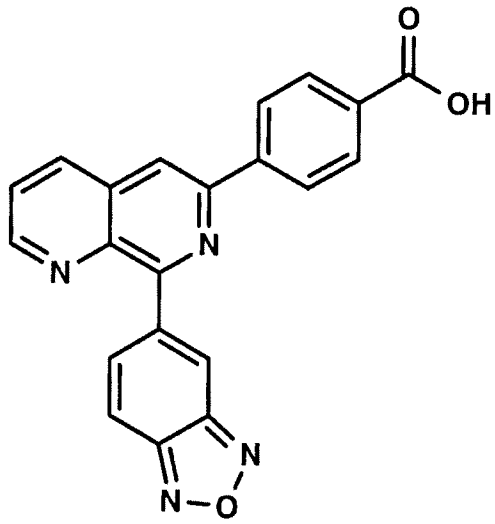

Fig. 1. Structure of NVP-ABE171.

TABLE 1

Inhibition of human phosphodiesterase activity by NVP-ABE171 and related compounds

Data are expressed as mean ± S.E.M. from the number of experiments indicated in parentheses.

	IC_{50}			
	NVP-ABE171	Ariflo	V 11294A	LAS 31025
	nM			
PDE4A	602 ± 25 (4)	398 ± 7 (4)	446 ± 11 (3)	2614 ± 48 (3)
PDE4B	34 ± 0.5 (3)	288 ± 7 (3)	616 ± 7 (3)	1452 ± 52 (3)
PDE4C	1230 ± 39 (3)	813 ± 13 (4)	1698 ± 44 (3)	1995 ± 38 (3)
PDE4D	1.5 ± 0.1 (4)	63 ± 2 (4)	645 ± 14 (3)	965 ± 8 (3)
PDE1	>10,000 (2)	>10,000 (2)	>10,000 (2)	>10,000 (2)
PDE2	>10,000 (2)	>10,000 (2)	>10,000 (2)	>10,000 (2)
PDE3	>10,000 (2)	>10,000 (2)	>10,000 (2)	>10,000 (2)
PDE5	>10,000 (2)	>10,000 (2)	>10,000 (2)	>10,000 (2)

TABLE 2

Effects of NVP-ABE171 and related compounds on functional responses of human inflammatory cells

Data are expressed as mean ± S.E.M. from the number of experiments indicated in parentheses.

	IC_{50}		
	NVP-ABE171	Ariflo	V 11294A
		nM	
Eosinophil function			
Oxidative burst (IgG)	6.0 ± 0.2 (4)	104.7 ± 5.3 (3)	712 ± 19 (3)
T-Cell cytokines release			
INF-γ (anti-CD3)	10.0 ± 0.2 (5)	257.1 ± 7.6 (4)	1905 ± 63 (3)
IL-4 (anti-CD3)	16.6 ± 0.3 (5)	389.0 ± 8.5 (4)	2089 ± 51 (3)
IL-5 (anti-CD3)	28.2 ± 0.5 (5)	199.5 ± 9.2 (4)	2754 ± 94 (3)
Monocytes cytokine release			
TNF-α (IFN-γ + LPS)	67.6 ± 1.0 (3)	3467 ± 64 (3)	4365 ± 49 (3)

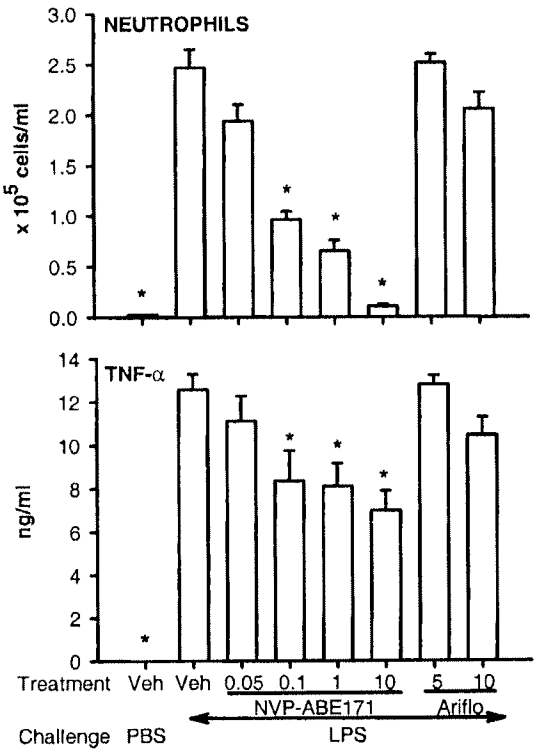

Fig. 2. Effect of NVP-ABE171 and Ariflo on LPS-induced airway inflammation 3 h after the intranasal challenge in mice. NVP-ABE171 (0.05–10 mg kg^{-1}) and Ariflo (5–10 mg kg^{-1}) were given orally 1 h before the LPS exposure. Three hours after the LPS challenge, animals were sacrificed and bronchoalveolar lavage was performed. Results are expressed as means ± S.E.M. of two different experiments, each including 6 to 10 animals/group. Statistical significance (*, $P < 0.05$) was assessed against the vehicle-treated (Veh) and LPS-challenged animals. Doses are expressed in milligrams per kilogram.

pranolol (52.6 ± 9.5 10^{-5} cm/s, $n = 4$). As expected for a PDE4 inhibitor, NVP-ABE171 enhanced the accumulation of cAMP in human HaCat cells induced by isoprenaline with an EC_{200} value of 3.5 ± 0.9 nM ($n = 3$). Because the other compounds are well characterized PDE4 inhibitors, they were not tested in these assays.

Inhibition of Cell Function in Vitro. Because of its very low potency in the enzyme-based assay, LAS 31025 was not studied further. In line with the enzyme inhibition data, V 11294A was a very weak inhibitor of the inflammatory cells' activation (Table 2).

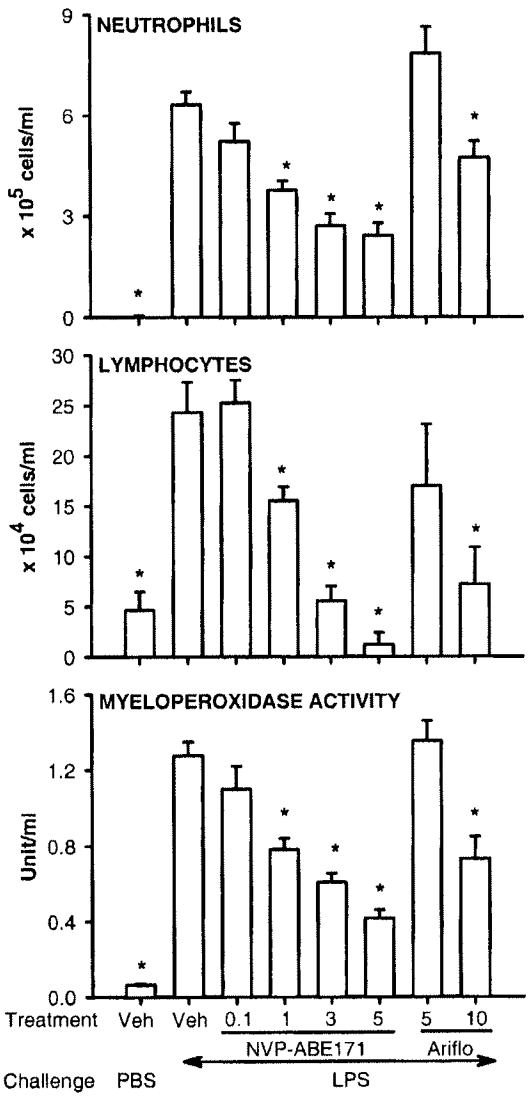

Fig. 3. Effect of NVP-ABE171 and Ariflo on LPS-induced airway inflammation 24 h after the intranasal challenge in mice. NVP-ABE171 (0.1–5 mg kg^{-1}) and Ariflo (5–10 mg kg^{-1}) were given orally 1 h before and 6 h after the LPS exposure. Twenty-four hours after the LPS challenge, animals were sacrificed and bronchoalveolar lavage was performed. Results are expressed as means ± S.E.M. of two to three different experiments, each including 6 to 10 animals/group. Statistical significance (*, $P < 0.05$) was assessed against the vehicle-treated (Veh) and LPS-challenged animals. Doses are expressed in milligrams per kilogram.

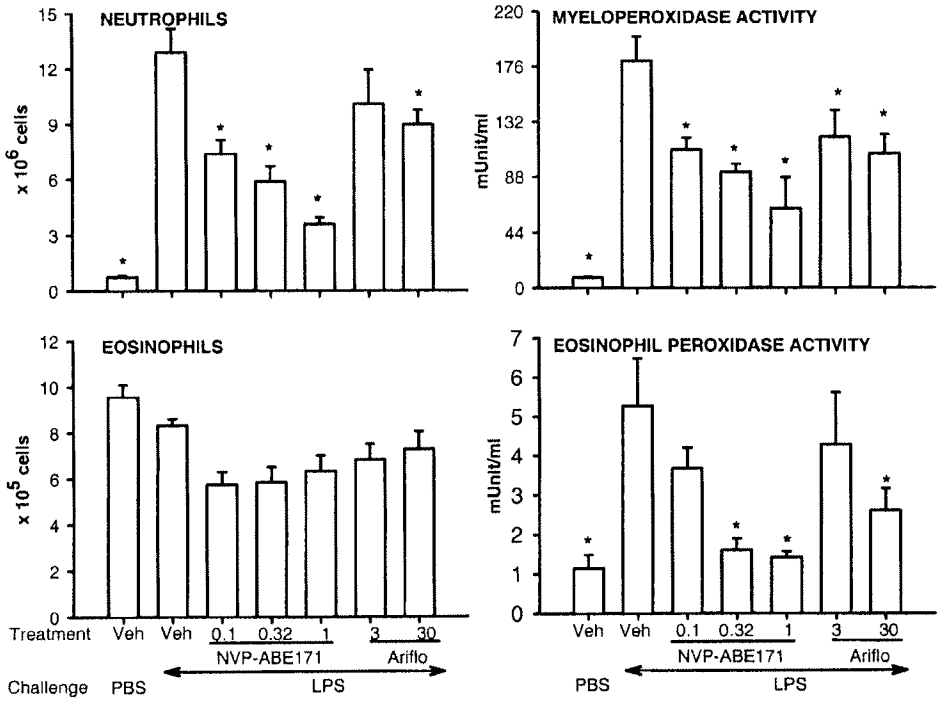

Fig. 4. Effect of NVP-ABE171 and Ariflo on LPS-induced airway inflammation 24 h after the intratracheal challenge in rats. NVP-ABE171 (0.1–1 mg kg^{-1}) and Ariflo (3 and 30 mg kg^{-1}) were given orally 1 h before the LPS exposure. Twenty-four hours after the LPS exposure, animals were sacrificed and bronchoalveolar lavage was performed. Results are expressed as means ± S.E.M. of two different experiments, each including 5 to 10 animals/group. Statistical significance (*, $P < 0.05$) was assessed against the vehicle-treated (Veh) and LPS-challenged animals. Doses are expressed in milligrams per kilogram.

NVP-ABE171 fully suppressed all the measured functional responses of human eosinophils, T cells, and monocytes with IC_{50} values in the nanomolar range (Table 2). Ariflo also fully suppressed these responses, but showed lower potencies (7 to 50 times less potent) than NVP-ABE171 (Table 2). In contrast to the other cell types' functions, NVP-ABE171 and Ariflo inhibited the neutrophil oxidative burst to a maximum of about 50% under the conditions used. Therefore, for quantitative analysis IC_{25} values were calculated (NVP-ABE171, 1.5 ± 0.09 nM; and Ariflo, 65.5 ± 5.4 nM, $n = 4$). Because V 11294A and LAS 31025 were very weak PDE4 inhibitors in vitro, we decided not to pursue their characterization in vivo.

Inhibition of LPS-Induced Lung Inflammation in Mice. At 3 h postprovocation, LPS induced a marked increase in neutrophil numbers and TNF-α levels in the bronchoalveolar lavage. No changes in the other cell types (macrophages, eosinophils, and lymphocytes) were observed (data not shown). Oral administration of NVP-ABE171, 1 h before the challenge, induced a dose-dependent inhibition of the neutrophil influx with an ED_{50} value of 0.08 mg/kg (Fig. 2). The LPS-induced TNF-α release was only partially inhibited by NVP-ABE171 and no ED_{50} could be calculated (Fig. 2). Ariflo at both 5 and 10 mg/kg was inactive on all the parameters studied (Fig. 2).

At 24 h postprovocation, LPS induced a marked increase in neutrophil and lymphocyte numbers. No changes in the other cell types (macrophages and eosinophils) were observed (data not shown). Oral administration of NVP-ABE171, 1 h before and 6 h after the challenge, induced a dose-dependent inhibition of these two parameters with an ED_{50} value of 2.8 and 1.5 mg/kg for the neutrophil and lymphocyte influx, respectively (Fig. 3). In parallel with the number of neutrophils, the levels of myeloperoxidase activity as a measure of neutrophil degranulation were also dose dependently inhibited by NVP-ABE171 with an ED_{50} value of 3.2 mg/kg (Fig. 3). Ariflo was able to inhibit all the parameters studied only at 10 mg/kg (Fig. 3).

Inhibition of LPS-Induced Lung Inflammation in Brown Norway Rat. Oral administration of NVP-ABE171 given 1 h before LPS exposure dose dependently inhibited the infiltration and activation, as measured by myeloperoxidase activity levels, of neutrophils recovered in the bronchoalveolar lavage 24 h after LPS challenge. The ED_{50} value for both parameters was 0.2 mg/kg (Fig. 4). In addition to its neutrophil infiltration-suppressing activity, the compound also reduced the activity of eosinophil peroxidase activity recovered in the bronchoalveolar lavage of LPS-challenged animals (ED_{50} value of 0.13 mg/kg) without affecting the number of eosinophils (Fig. 4). Oral administration of Ariflo (3 and 30 mg kg^{-1}) given 1 h before LPS challenge inhibited the infiltration and activation of neutrophils recovered in bronchoalveolar lavage fluid 24 h after LPS challenge, displaying a flat dose relationship. Reductions in the activity of eosinophil peroxidase activity were also seen (Fig. 4).

Inhibition of Ovalbumin-Induced Lung Inflammation in Rat. Forty-eight hours after ovalbumin challenge, there was a pronounced infiltration of eosinophils into the airways of sensitized Brown Norway rats, accompanied by increases in bronchoalveolar lavage eosinophil peroxidase activity and proteins. Oral administration of NVP-ABE171, 1 h before and 24 h after antigen challenge, induced dose-dependent inhibition of the numbers of eosinophils, eosinophil peroxidase activity, and plasma-derived protein levels in bronchoalveolar lavage (Fig. 5). The ED_{50} value for the changes in eosinophil numbers was 0.1 mg/kg. Similar ED_{50} values were obtained for the inhibition of eosinophil peroxidase activity (0.1 mg/kg) and protein levels (0.2 mg/kg) in bronchoalveolar lavage.

NVP-ABE171 also reduced the numbers of neutrophils and lymphocytes in bronchoalveolar lavage after oral administra-

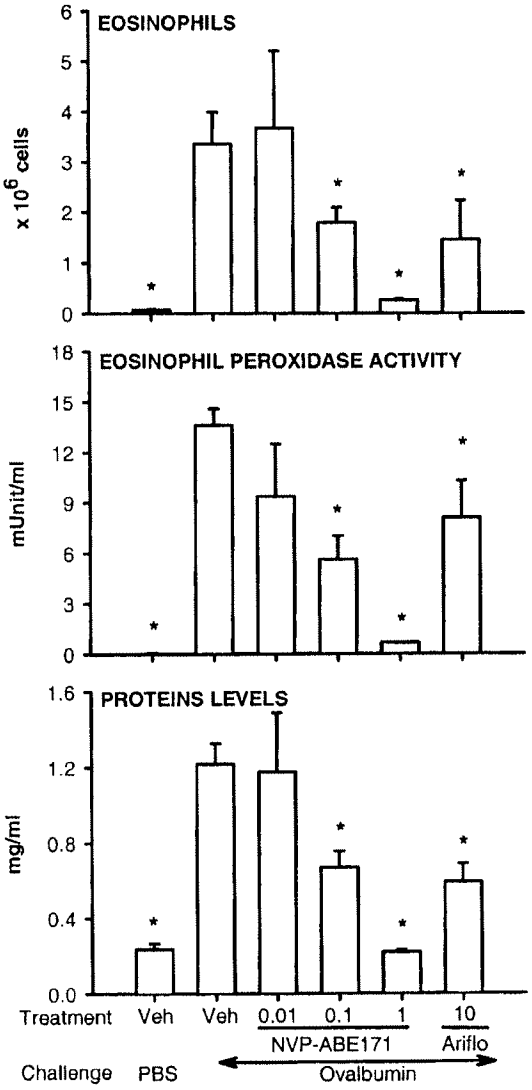

Fig. 5. Effect of NVP-ABE171 and Ariflo on the ovalbumin-induced airway inflammation 48 h after the aerosol challenge in rats. NVP-ABE171 (0.01–1 mg kg^{-1}) and Ariflo (10 mg kg^{-1}) were given orally 1 h before and 24 h after the ovalbumin exposure. Forty-eight hours after the ovalbumin exposure, animals were sacrificed and bronchoalveolar lavage was performed. Results are expressed as means ± S.E.M. of two different experiments, each including 5 to 10 animals/group. Statistical significance (*, $P < 0.05$) was assessed against the vehicle-treated (Veh) and ovalbumin-challenged animals. Doses are expressed in milligrams per kilogram.

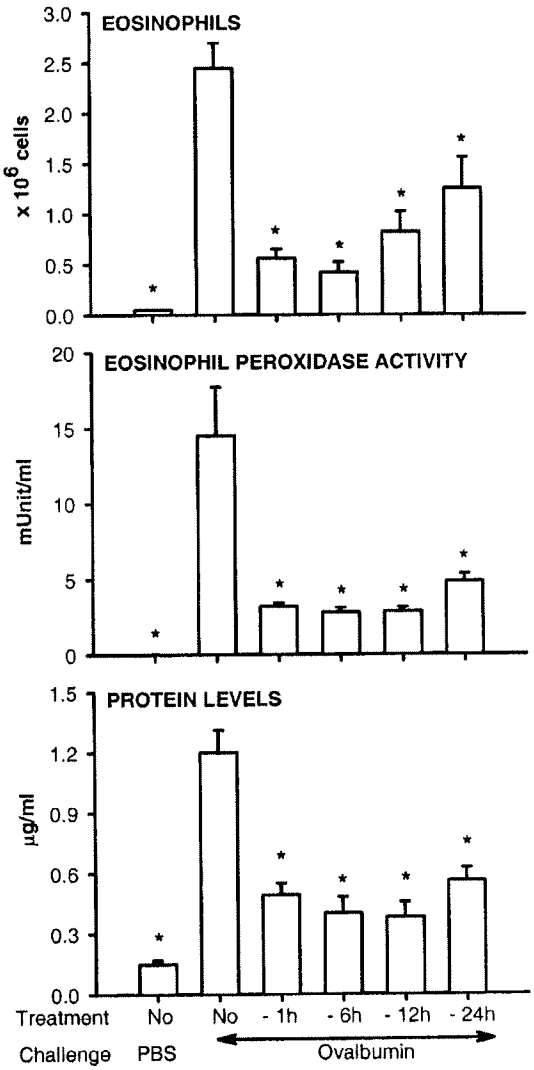

Fig. 6. Duration of action of NVP-ABE171 on the ovalbumin-induced airway inflammation in rats. NVP-ABE171 (0.4 mg kg^{-1}) was given orally from 1 to 24 h before the ovalbumin challenge. Twenty-four hours after the ovalbumin exposure, animals were sacrificed and bronchoalveolar lavage was performed. Results are expressed as means ± S.E.M. of one experiment including 5 to 10 animals/group. Statistical significance (*, $P < 0.05$) was assessed against the untreated (No) and ovalbumin-challenged animals.

tion 1 h before and 24 h after allergen challenge. Again, the ED_{50} values calculated from the dose-response curves were similar to those required to inhibit eosinophil infiltration (data not shown).

Ariflo, at 10 mg/kg, was substantially less active in this model than NVP-ABE171, although the effects were qualitatively similar (Fig. 5). Thus, by using eosinophil numbers in bronchoalveolar lavage as the readout, the reduction seen with Ariflo after oral administration of 10 mg/kg 1 h before and 24 h after allergen challenge was 44%.

Duration of Action of NVP-ABE171 in Ovalbumin-Induced Lung Inflammation in Rat. The ovalbumin-induced increase in eosinophil numbers, eosinophil peroxidase activity, and protein levels recovered 24 h after the allergen challenge was significantly inhibited by 0.4 mg/kg NVP-ABE171 administered 1, 6, 12, and 24 h before the challenge (Fig. 6). A similar duration of action on the reduction in total cells, neutrophils, and lymphocytes was also evident (Table 3). Ariflo (30 mg/kg) was inactive when given 6 h before the challenge (data not shown).

Discussion

Chronic obstructive pulmonary disease and asthma are two inflammatory disorders of the airways. Chronic obstructive pulmonary disease is characterized by airway obstruction that is slowly progressive and irreversible. This disease encompasses two related conditions: chronic bronchitis and emphysema. Chronic bronchitis is characterized by mucus

hypersecretion and increased risk of chest infections. Approximately 15% of smokers develop progressive airflow limitation that is largely due to enzymatic destruction of elastin fibers in the lung parenchyma (emphysema). Both conditions have an inflammatory component that is characterized by infiltration of neutrophils and macrophages into the lungs (Jeffery, 1998). Bronchial asthma is a chronic inflammatory disease of the airways, a prominent feature of which is an intense infiltration of eosinophils and mononuclear cells (Djukanovic et al., 1990).

PDE4 inhibitors have been shown to be potent anti-inflammatory agents in various animal models (Teixeira et al., 1997) and also have shown clinical efficacy in both asthma and chronic obstructive lung diseases (Torphy et al., 1999). Analysis of a number of human cell lines or defined blood cell populations revealed clear differences in the PDE4 isotype expression pattern in the immune system (Muller et al., 1996). As such, PDE4C could not be detected in any of the immune cells, whereas PDE4A and 4B expression were seen in the majority of the immune cells. PDE4D was mainly expressed in eosinophils and to a lesser extent in neutrophils. Based on all this information, we designed PDE4 inhibitors displaying different selectivity profiles against the PDE4 isozymes (Hersperger et al., 2000) and as a result of this strategy, NVP-ABE171, a selective inhibitor for PDE4B and 4D, was selected for further profiling.

Because PDE4 inhibitors have the potential to be efficacious in both asthma and chronic obstructive pulmonary disease, we next tested the efficacy of NVP-ABE171 on different human leukocytes known to be involved in these two diseases. As such, the asthmatic airway inflammation is driven by T cells and eosinophils are believed to be one of the terminal effector cells in this disease (Djukanovic et al., 1990). On the other hand, in patients with chronic obstructive pulmonary disease the inflammatory cells involved are neutrophils and macrophages (Jeffery, 1998). In agreement with the enzyme-based data, Ariflo was about 10 to 50 times less potent than NVP-ABE171, depending on the cell types used. Compared with the other leukocytes investigated, monocytes and neutrophils seem to be more resistant to inhibition by both compounds. Indeed, for both compounds, the potency on monocytes was lower compared with eosinophils or T cells and the neutrophil oxidative burst could be inhibited to a maximum of 50%. This has already been reported for other PDE4 inhibitors (Hatzelmann and Schudt, 2001) and one can argue that it may be a therapeutic advantage, because both macrophages and neutrophils are important immune cells in the host defense process.

We next investigated the in vivo efficacy of NVP-ABE171 and Ariflo in animal models of lung inflammation by using both mice and rats. Because V 11294A and LAS 31025 were weak PDE4 inhibitors in vitro we decided not to characterize them in vivo. Because drugs that are aimed at treating chronic inflammation in humans should be administered daily, orally active compounds are highly desirable as therapeutics. We therefore tested the effect of NVP-ABE171 by the oral route. Because chronic obstructive pulmonary disease is characterized by an increase in the activation and/or numbers of neutrophils and macrophages, it was important to test NVP-ABE171 in a macrophage-dependent in vivo model. To do so, we used the LPS-induced lung inflammation model that has been shown to be dependent upon macrophage activation, and more importantly, to be inhibited by rolipram, the archetype of PDE4 inhibitors (Goncalves de Moraes et al., 1998). In both mice and rats, NVP-ABE171 potently inhibited the neutrophil influx and their activation observed 24 h after the LPS challenge. Ariflo also inhibits these parameters, however, with a much lower potency. Because it has been shown that treatment with cAMP-elevating agents inhibits the TNF-α production in a murine LPS model (Goncalves de Moraes et al., 1996), it was somewhat surprising to see that NVP-ABE171 was not very potent at inhibiting the LPS-induced TNF-α release in the mice. This observation is in line with the results obtained in our cell-based assay showing that from all the inflammatory cells tested, monocytes were the least responsive to inhibition by NVP-ABE171. Furthermore, it has been shown in vitro that to efficiently inhibit the LPS-induced TNF-α release from macrophages, an inhibition of PDE4 and PDE3 was necessary (Gantner et al., 1997). Nevertheless, we clearly showed that NVP-ABE171, in two different species (mice and rats) is a powerful inhibitor of both the migration of neutrophil into the airways and their activation. It is interesting to note that NVP-ABE171 was effective in suppressing the neutrophilia at both 3 and 24 h postchallenge, whereas Ariflo inhibited the neutrophil influx only at the late time point. We do not have any explanation for this phenomenon. However, in line with our results, Ariflo has been reported to be less potent in inhibiting the early phase (2 h) of the LPS-induced airway inflammation in rat compared with the latest phase (24 h) (Spond et al., 2001).

Ovalbumin inhalation to actively sensitized rats is a well characterized and recognized model for asthma (Renzi et al., 1993). This acute inflammatory model is characterized by an influx of leukocytes and plasma accumulation into the airways, two conditions seen in human asthma (Djukanovic et al., 1990). NVP-ABE171 dose dependently and potently inhibited the allergen-induced increase in airway plasma pro-

TABLE 3

Duration of action of NVP-ABE171 (0.4 mg kg^{-1}) on ovalbumin-induced increase in total cell, lymphocyte, and neutrophil in rat airways

Results are expressed as means ± S.E.M.

Treatment/Challenge	n	Cell Counts (10^6)		
		Total Cells	Lymphocytes	Neutrophils
Non-treated/PBS	5	4.80 ± 0.38*	0.27 ± 0.02*	0.14 ± 0.02*
Non-treated/ovalbumin	10	10.60 ± 1.92	1.95 ± 0.38	1.52 ± 0.29
−1 h/ovalbumin	10	4.66 ± 0.45*	0.54 ± 0.08*	0.38 ± 0.07*
−6 h/ovalbumin	10	4.40 ± 0.33*	0.52 ± 0.07*	0.38 ± 0.06*
−12 h/ovalbumin	10	5.40 ± 0.66*	0.78 ± 0.13*	0.69 ± 0.15*
−24 h/ovalbumin	10	6.54 ± 0.91*	1.14 ± 0.17*	0.77 ± 0.19*

Statistical significance (* $P < 0.05$) was assessed against the vehicle-treated and ovalbumin-challenged animals.

tein accumulation. The inhibitory mechanism of action of such compounds on plasma exudation is still unclear; however, other PDE4 inhibitors have been reported to inhibit plasma leakage in vivo through the inhibition of the endothelial cell contraction (Ortiz et al., 1996). NVP-ABE171 was also very potent at inhibiting the influx of inflammatory leukocytes and their activation. Because PDE4 inhibitors are known to have a powerful modulating activity on virtually all cells involved in the inflammatory process (Teixeira et al., 1997), it is quite difficult to dissect out their precise anti-inflammatory mechanism of action in this model. However, the main effect of NVP-ABE171 in this model is rather likely to be due to the inhibition of T-cell activation, which are the cells known to drive the inflammatory process in this model (Underwood et al., 1997). In addition to its greater potency compared with Ariflo, NVP-ABE171 also has a much longer duration of action. As such, in the Brown Norway rat, the inhibitory effect of Ariflo was lost when given 6 h before the allergen challenge (data not shown), whereas NVP-ABE171 had a duration of action of more than 24 h. Because Ariflo is administered twice a day in the clinic, these data suggest that NVP-ABE171 could be a once-a-day drug.

During the preparation of this manuscript, the preclinical data for roflumilast (3-cyclopropylmethoxy-4-difluoromethoxy-*N*-[3,5-dichloropyrid-4-yl]-benzamide), a PDE4 inhibitor in clinical development administered once a day, were published (Bundschuh et al., 2001; Hatzelmann and Schudt, 2001). Compared with Ariflo, this compound was reported to be 50 to 100 times more potent in in vitro assays (Hatzelmann and Schudt, 2001) and about 50 times more potent in inhibiting the ovalbumin-induced lung inflammation in the Brown Norway rat (Bundschuh et al., 2001). In this model, its duration of action was reported to be more than 18 h (Bundschuh et al., 2001). YM976 is another PDE4 inhibitor in clinical development and a comprehensive package of preclinical data has been published for this compound (Aoki et al., 2000a,b, 2001). Compared with Ariflo, YM976 has been shown to be about 50 times more potent in vitro. However, when tested in vivo, YM976 was only 10 times more potent than Ariflo (Aoki et al., 2000). Although we did not compare NVP-ABE171 with roflumilast and YM967 in the present study, based on the published data, NVP-ABE171 seems to be 10 times more potent than YM976 in vivo and at least as potent as roflumilast with a similar duration of action in vivo.

In summary, the preclinical data presented in this report indicate that NVP-ABE171 is a potent orally active PDE4D inhibitor with a long duration of action in vivo. Thus, PDE4 inhibitors from the 6,8-disubstituted 1,7-naphthyridine class may have potential for the treatment of inflammatory lung diseases such as asthma and chronic obstructive pulmonary disease.

References

Aoki M, Fukunaga M, Kitagawa M, Hayashi K, Morokata T, Ishikawa G, Kubo S, and Yamada T (2000a) Effect of a novel anti-inflammatory compound, YM976, on antigen-induced eosinophil infiltration into the lungs in rats, mice, and ferrets. *J Pharmacol Exp Ther* **295:**1149–1155.

Aoki M, Kobayashi M, Ishikawa J, Saita Y, Terai Y, Takayama K, Miyata K, and Yamada T (2000b) A novel phosphodiesterase type 4 inhibitor, YM976 (4-(3-chlorophenyl)-1,7-diethylpyrido[2,3-d]pyrimidin-2(1*H*)-one), with little emetogenic activity. *J Pharmacol Exp Ther* **295:**255–260.

Aoki M, Yamamoto S, Kobayashi M, Ohga K, Kanoh H, Miyata K, Honda K, and Yamada T (2001) Antiasthmatic effect of YM976, a novel PDE4 inhibitor, in guinea pigs. *J Pharmacol Exp Ther* **297:**165–173.

Barnes PJ (1999) Therapeutic strategies for allergic diseases. *Nature (Lond)* **402:** B31–B38.

Beavo JA (1995) Cyclic nucleotide phosphodiesterases: functional implications of multiple isoforms. *Physiol Rev* **75:**725–748.

Bundschuh DS, Eltze M, Barsig J, Wollin L, Hatzelmann A, and Beume R (2001) In vivo efficacy in airway disease models of roflumilast, a novel orally active PDE4 inhibitor. *J Pharmacol Exp Ther* **297:**280–290.

Djukanovic R, Roche WR, Wilson JW, Beasley CR, Twentyman OP, Howarth RH, and Holgate ST (1990) Mucosal inflammation in asthma. *Am Rev Respir Dis* **142:**434–457.

Engels P, Sullivan M, Muller T, and Lubbert H (1995) Molecular cloning and functional expression in yeast of a human cAMP-specific phosphodiesterase subtype (PDE IV-C). *FEBS Lett* **358:**305–310.

Gantner F, Kupferschmidt R, Schudt C, Wendel A, and Hatzelmann A (1997) In vitro differentiation of human monocytes to macrophages: change of PDE profile and its relationship to suppression of tumour necrosis factor-alpha release by PDE inhibitors. *Br J Pharmacol* **121:**221–231.

Goncalves de Moraes V, Boris VB, Lefort J, Meager A, and Chignard M (1996) Effect of cyclo-oxygenase inhibitors and modulators of cyclic AMP formation on lipopolysaccharide-induced neutrophil infiltration in mouse lung. *Br J Pharmacol* **117:** 1792–1796.

Goncalves de Moraes V, Singer M, Vargaftig BB, and Chignard M (1998) Effects of rolipram on cyclic AMP levels in alveolar macrophages and lipopolysaccharide-induced inflammation in mouse lung. *Br J Pharmacol* **123:**631–636.

Hannon JP, Tigani B, Williams I, Mazzoni L, and Fozard JR (2001) Mechanism of airway hyperresponsiveness to adenosine induced by allergen challenge in actively sensitized Brown Norway rats. *Br J Pharmacol* **132:**1509–1523.

Hatzelmann A and Schudt C (2001) Anti-inflammatory and immunomodulatory potential of the novel PDE4 inhibitor roflumilast in vitro. *J Pharmacol Exp Ther* **297:**267–279.

Hersperger R, Bray-French K, Mazzoni L, and Muller T (2000) Palladium-catalyzed cross-coupling reactions for the synthesis of 6, 8-disubstituted 1,7-naphthyridines: a novel class of potent and selective phosphodiesterase type 4D inhibitors. *J Med Chem* **43:**675–682.

Jeffery PK (1998) Structural and inflammatory changes in COPD: a comparison with asthma. *Thorax* **53:**129–136.

Muller T, Engels P, and Fozard JR (1996) Subtypes of the type 4 cAMP phosphodiesterases: structure, regulation and selective inhibition. *Trends Pharmacol Sci* **17:**294–298.

Ortiz JL, Valles JM, Marti-Cabrera M, Cortijo J, and Morcillo EJ (1996) Effects of selective phosphodiesterase inhibitors on platelet-activating factor- and antigen-induced airway hyperreactivity, eosinophil accumulation, and microvascular leakage in guinea pigs. *Naunyn-Schmiedeberg's Arch Pharmacol* **353:**200–206.

Renzi PM, Olivenstein R, and Martin JG (1993) Effect of dexamethasone on airway inflammation and responsiveness after antigen challenge of the rat. *Am Rev Respir Dis* **148:**932–939.

Soderling SH and Beavo JA (2000) Regulation of cAMP and cGMP signaling: new phosphodiesterases and new functions. *Curr Opin Cell Biol* **12:**174–179.

Spond J, Chapman R, Fine J, Jones H, Kreutner W, Kung TT, and Minnicozzi M (2001) Comparison of PDE 4 inhibitors, rolipram and SB 207499 (Ariflo), in a rat model of pulmonary neutrophilia. *Pulm Pharmacol Ther* **14:**157–164.

Teixeira MM, Gristwood RW, Cooper N, and Hellewell PG (1997) Phosphodiesterase (PDE)4 inhibitors: anti-inflammatory drugs of the future? *Trends Pharmacol Sci* **18:**164–171.

Torphy TJ, Barnette MS, Underwood DC, Griswold DE, Christensen SB, Murdoch RD, Nieman RB, and Compton CH (1999) Ariflo (SB 207499), a second generation phosphodiesterase 4 inhibitor for the treatment of asthma and COPD: from concept to clinic. *Pulm Pharmacol Ther* **12:**131–135.

Underwood SL, Raeburn D, Lawrence C, Foster M, Webber S, and Karlsson JA (1997) RPR 106541, a novel, airways-selective glucocorticoid: effects against antigen-induced CD4+ T lymphocyte accumulation and cytokine gene expression in the Brown Norway rat lung. *Br J Pharmacol* **122:**439–446.

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